ULTRASONIC NDE OF LAYERED COMPOSITES USING PULSED LASER

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INTRODUCTION

The present paper is concerned with the ultrasonic inspection of composite panels, fabricated by attaching a thin (<1mm) layer of aluminium to a rigid foam substrate using an epoxy resin, and of composite materials, consisting of aluminium sheets bonded together with an epoxy adhesive layer. These materials are represented schematically in Figs. 1(a) and 1(b) respectively. The characterization of such materials involves the detection of a delamination at an aluminium/epoxy interface, and the measurement of the properties of the epoxy layer, which may be affected by curing conditions and chemical composition.

Several approaches are possible, such as time domain analysis, low frequency impedance technique, the so-called "coin-tap" method or spectroscopy analysis [1,2]. A conventional method would use a C-scan ultrasonic test, which forms an image of the structure at a given depth into the sample. However, many problems arise when interfaces of a complex multilayered material, composed of several attenuating media, have to be tested. Indeed, the usual large acoustic mismatches (i.e. impedance changes) across the interfaces tend to generate strong multiple reflections, masking reflections from underlying layers [3]. Also the strong absorption in the bonding layers limits the amplitude (and hence accuracy) of the returning echoes from the lower interfaces.

We have thus investigated other methods which could be used. The first involves sending transient Lamb waves along the top aluminium layer, whose form depends on the damping by the epoxy layer. The second method uses multiple reflections within the multilayered composite to set up a resonance whose form is again sensitive to the integrity of the material. Conventional techniques usually involve some form of contacting transducer or the use of immersion method. These methods are, however, difficult to use for wide bandwith generation. For this reason, a pulsed laser for ultrasonic generation [4] has been used. The two approaches will now be described separately in turn.

USE OF TRANSIENT LAMB WAVES

Principles

There are various classes of waves which can propagate in directions parallel to the aluminium/epoxy interfaces. These include longitudinal and shear modes within each layer (including the case of Love (SH) waves), waves along the two interfaces (lateral and Stoneley waves) and generalized Lamb waves in the aluminium [5]. Each of these modes may have application to the testing of bond quality. Rokhlin et al [6] have examined propagation of this type, and some results have been applied to study aluminium/epoxy bonds [7].

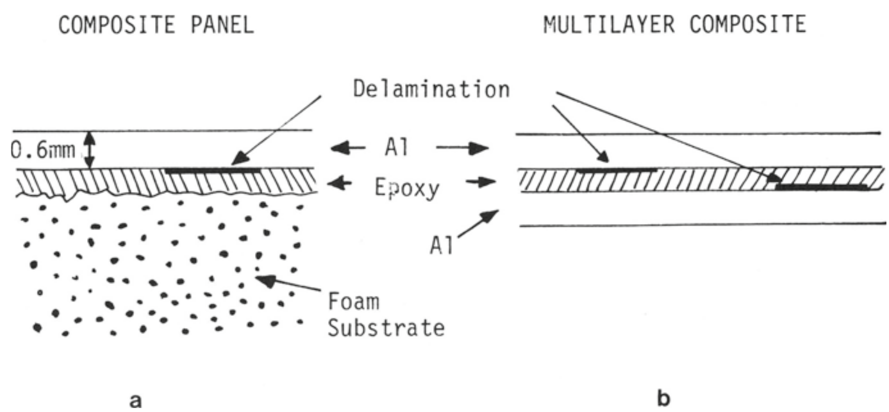

Figure 1. Multilayered materials under study : (a) composite panel and (b) composite consisting of two aluminium sheet bonded together with an epoxy adhesive layer.

The first approach that has been investigated is primarily concerned with Lamb waves [5] that travel along the top aluminium plate. These waves are classified in terms of certain modes, and it is the presence and the form of these modes that forms the basis of the present inspection technique. For the thickness of aluminium plates under consideration, the two lowest-order modes are expected to be dominant. These are known as the a_0 and s_0 modes, and their displacement in a free plate are shown in Fig. 2(a). The a_0 mode, also known as a "flexural wave", has a large vertical motion. The s_0 mode, or "extensional wave", has a large motion parallel to the plate surface. The phase velocity C of these modes can be calculated, and is given for a Poisson's ratio ν=0.34 in Fig. 2(b), together with the higher modes (a_1, s_1, s_2, etc.). On Fig. 2(b), k is the wavenumber, h the plate thickness, and C_T is the shear wave velocity. There are several features to note. For a low value of the product kh, the a_0 mode has a velocity which varies little with frequency. The a_0 mode, however, increases in velocity as k increases, h being constant, i.e. it is dispersive. The next two modes to appear (s_1 and a_1) do not exist below a certain cut-off frequency, at which they experience high attenuation.

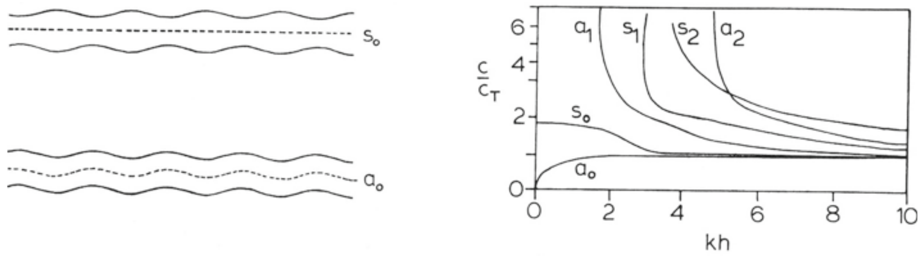

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Figure 2. (a) Schematic representation of the two first Lamb modes, namely the a_0 and s_0 modes; (b) dispersion relations for the first three orders of Lamb modes, where C is the Lamb wave phase velocity.

Use of a transient source, with enough bandwith, would cause a number of these modes to be generated. As the epoxy would cause preferential attenuation of higher frequencies, it would be expected that proper adhesion via a competent bond line would cause the amplitude of higher-order modes to decrease.

Apparatus

A first set of experiments were conducted using a pulsed laser for ultrasonics generation and an electromagnetic acoustic transducer (EMAT) for detection. The laser was a Q-switched ruby laser with a 30ns pulse length at 694nm and a 500mJ maximum optical energy. The beam was focused to a line source ($\approx$ 0.1mm wide and 25mm long) on the surface of the sample, as shown in Fig. 3. In order to generate an impulsive vertical force, the specimen surface was coated with oil [8]. The receiver was a specially constructed EMAT for the detection of horizontal motion [9], and was operating in a line geometry (Fig. 3). This type of geometry allowed the propagation along a specific direction of the plate to be optimized.

The method was also implemented using commercial piezoelectric transducers. Two Panametrics 2.25 MHz contact shear-wave transducers were fitted with brass end-caps, machined to a line contact of approximate dimensions 20mm x 1mm. These were used in the pitch-catch mode, being driven by a Panametrics 5055PR pulser unit. This produced good sensitivity at frequencies beyond 3 MHz.

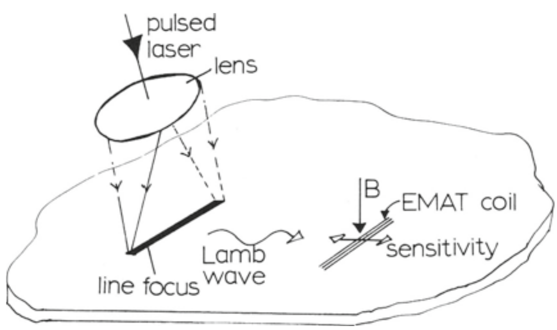

Figure 3. Schematic diagram of apparatus. A ruby laser beam was focused to a line source and the receiver was an electromagnetic transducer (EMAT) for the detection of vertical motion.

Results

Experiments, conducted with the composite panel of Fig. 1(a), are presented in this section. Consider first the waveform presented in Fig. 4(a). This was recorded at a position on the panel where a good bond existed, using the laser generation technique described in Fig. 3. The s_0 mode arrives first, in the form of a wide bandwith pulse, showing little dispersion. The a_0 mode follows, exhibiting the dispersion expected from the above discussion and other previous study [10]. Note that these are the only modes present, higher modes being absent. At a region of disbond, Fig. 4(b), additional high frequency components are present, due to contributions from the higher order modes. Their presence is confirmed after inspecting the spectrum of the time waveform, shown in Fig. 4(c). The presence of high frequencies thus serves as a test for disbond.

The second set of experiments was undertaken using the transducer arrangement described above. When positioned on a free aluminium plate of 0.8mm thickness, the received waveform had a spectrum shown in Fig. 5(a). Note that most of the energy is confined to frequencies below approximately 1 MHz, but that a distinct peak is present at 2.7-2.9 MHz, corresponding to a higher-order Lamb mode. When the probe assembly was placed over an area containing an adhered epoxy layer, the higher-order mode was attenuated, as shown in Fig. 5(b).

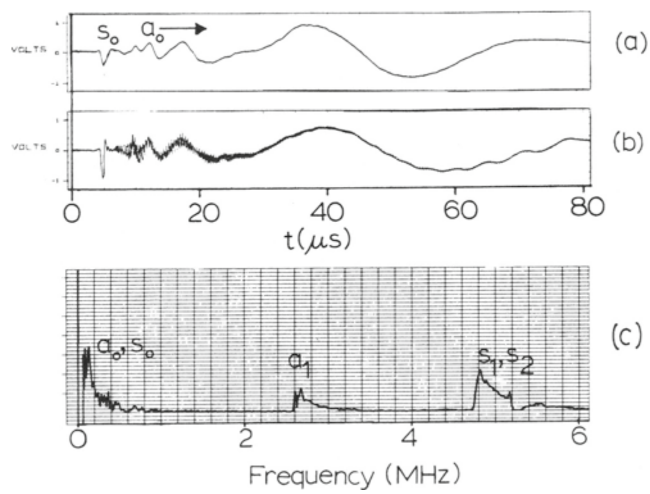

Figure 4. Time waveform obtained using the apparatus of Fig. 3 : (a) at a position where a good bond exist; (b) at a region of disbond. (c) Spectrum amplitude of the time waveform in (b).

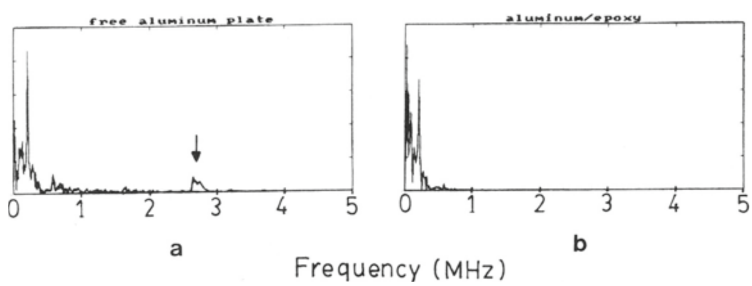

Figure 5. Spectra of waveforms using the transducer arrangement described in the text : (a) on a free aluminium plate of 0.8mm thickness and (b) at a position where a good bond exists.

USE OF THICKNESS RESONANCE TO EXAMINE MULTILAYERED MATERIALS

Guyott and Cawley [11] recently demonstrated that ultrasonic spectroscopy has considerable promise for the evaluation of the cohesive properties of a joint. The method consists of performing a frequency analysis of the signal reflected or transmitted in a specimen. In this previous study, a simplified model for a three layer sample was used and compared to experimental measurements obtained with immersion transducers. Here, a more complete model was used, allowing an arbitrary number of attenuating layers to be represented. The analysis was then applied to the characterization and non-destructive testing of multilayer systems.

Theory

The model used for the propagation and multiple reflection of elastic waves in an arbitrary multilayer system was based on the matrix transfer technique [12]. The problem is initially solved for an incident continuous plane wave originating in the above medium at an arbitrary angle. The method consists of using the boundary conditions from one layer to its neighbor, leading to the definition of a propagation matrix. By successive iterations, the overall multilayer material matrix can be constructed. Details can be found in reference [13]. This technique is particulary well suited for computer implementation and allows an arbitrary number of elastic layers to be modeled. Furthermore, the presence of absorption in a layer can be taken into account by having complex longitudinal and shear wave velocities [13]. By performing the calculations for a wide range of frequencies and by applying an inverse Fourier Transform, that can be efficiently computed with a FFT algorithm, an excitation by a wide-band source can readily be simulated. An acoustic beam of finite size can also be modeled by applying a spatial decomposition [14].

Using the model described above, predictions could be made. The properties of aluminium and epoxy used in the model are collected below

Material	Cp (m/s)	Cs (m/s)	$\rho(g/cm^3)$
Aluminium	6350	3100	2.7
Epoxy	2580	1100	1.3

Consider a typical specimen, sample J, composed of two 0.754mm thick aluminium plates bonded by a 0.560mm thick epoxy layer. The theoretical spectrum of the reflected signal is given in Fig. 6 and shows several amplitude minima, arising because of the different modes of resonance of the system (these minima would appear as maxima if the analysis was accomplished in the transmission mode [15] or if the large specular echo from the front surface was removed [16]). Some of the minima have been identified, and those corresponding to the epoxy layer are marked (Ep). Consequently, by analyzing the frequency spectrum of the reflected or transmitted signal for selected frequency values, information concerning a specific layer can be obtained. Moreover, the absence of a given mode of resonance could indicate the presence of a defect. Such an analysis provides a monitoring technique of multilayer materials.

The analysis of theoretical spectra showed another point of interest, that is the presence of a low frequency minimum, marked (Ov) in Fig. 6. This corresponds to the overall structure resonance [11], and could be of use in a fast monitoring test. Indeed, in the case of a delamination of any layer in the structure, the position of this resonance will be changed, and this can be easily detected by performing a spectral analysis. This type of measurement is quick to carry out and can give information about the integrity of the composite over its whole thickness.

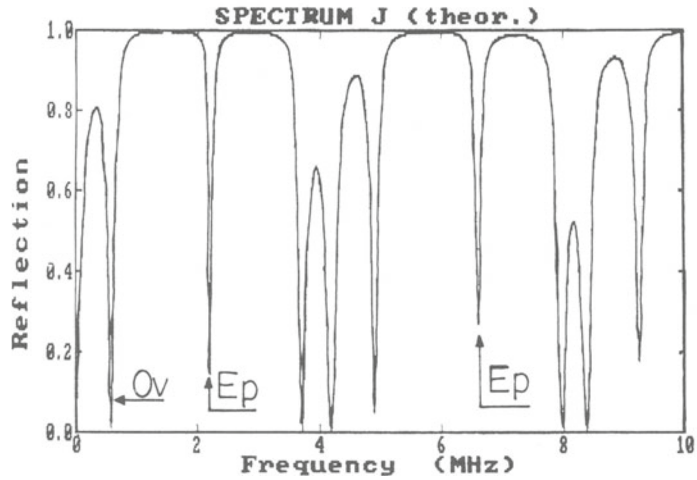

Figure 6. Theoretical frequency response of the reflection coefficient for sample J (consisting of two 0.754mm thick aluminium layers bonded by a 0.56mm thick epoxy layer).

Finally, since the knowledge of the whole frequency spectrum can be used to characterize the properties of each individual layer, this form of ultrasonic spectroscopy has the potential for inferring any information concerning the material properties and structure. It is important to realize that the best results will be obtained with a transmitting-receiving device having a bandwith as wide as possible, and hence the laser technique has been investigated for application to this problem.

Results

The remote laser technique was applied to the investigation of multilayer composites, such as described in Fig. 1(b). Trial experiments for a sample G, composed of two 0.754mm thick aluminium plates bonded by a 0.370mm thick epoxy layer, have shown good agreement between theory and experiment. The sample was excited using a Q-switched laser pulse, and the ultrasonic wave transmitted through the sample was detected by a conventional wide bandwith piezoelectric transducer (longitudinal, 5MHz).

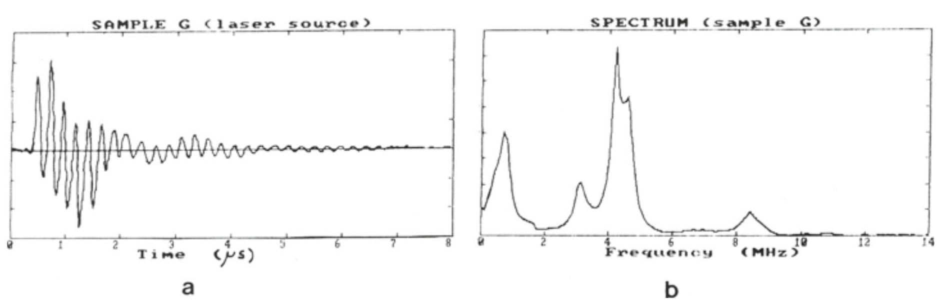

Figure 7. Measured response from sample G (two 0.754mm thick aluminium layers bonded by a 0.37mm thick epoxy layer) using a laser source and a 5 MHz receiver probe : (a) time waveform and (b) frequency spectrum.

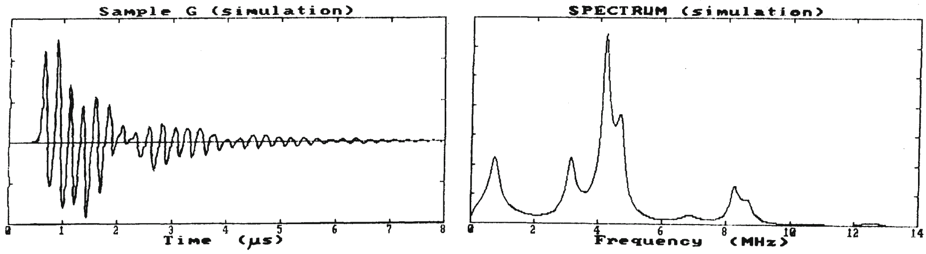

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Figure 8. Predicted response from a sample G (two 0.754mm thick aluminium layers bonded by a 0.37mm thick epoxy layer) using the theoretical analysis described in the text : (a) time waveform and (b) frequency spectrum.

An experimental waveform, obtained with such a set up, is shown in Fig. 7(a), and the corresponding spectrum is given in Fig. 7(b). The predicted waveform could be obtained by modeling the stucture with the theoretical analysis described above, and by performing a convolution between the theoretical impulse response and the experimental electoacoustic response of the 5 MHz Panametrics transducer. The attenuation in the epoxy layer was simulated by letting the imaginary part of the wave velocities to be 4% of the real part. The resulting time signal is presented in Fig. 8(a). Note the excellent agreement with the measured waveform of Fig. 7(a). The theoretical spectrum is presented in Fig. 8(b), and again shows good correlation with experiment (Fig. 7(b)).

A second set of experiments was undertaken using an annular EMAT detector, concentric with the laser beam. The sample under study had similar characteristics as sample J, described above. The reflected time waveform was first processed by removing the large specular echo from the front of the multilayer material, as it has been suggested [16]. This allows the resonance frequency to appear as a maximum [15], which is easier to detect than a minimum. When positioned on a well bonded area, the processed received signal spectrum had a spectrum shown in Fig. 9(a). Note that the overall structure resonance, around 420 KHz, is easily detected. When the probe assembly was placed over an area containing a delamination, this resonance disappeared, as shown in Fig. 9(b). The presence of this resonance thus can be used as a test for the integrity of the composite over its whole thickness.

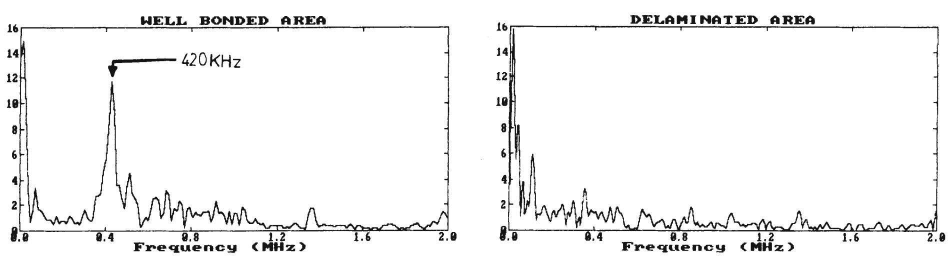

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Figure 9. Spectra of received waveforms using a laser source and an annular EMAT detector, concentric with the laser source : (a) assembly positioned on a well bonded area and (b) assemby placed over an area containing a delamination.

CONCLUSION

The above work has demonstrated that both Lamb wave and resonance methods have promise in the inspection of disbonds between aluminium and epoxy layers. It appears that for the investigation of multilayered materials, laser ultrasonics, in association with a frequency analysis technique, has several advantages over conventional techniques. Indeed, the remote laser technique is capable of high spatial resolution and a very wide bandwith (typically 0-15 MHz), which can be advantageously used in association with an ultrasonic spectroscopy method. This was evident in Fig. 7(b), where the resonance of the whole structure (arising at about 660 KHz) could be easily detected, as well as several other modes.

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